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B Physics at CDF

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B PHYSICS AT CDF

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B physics results from the CDF Collaboration based on data collected during the 1992-1996 Tevatron run are presented. In particular, we report the discovery of the B_c meson in the semileptonic decay $B_c \to J/\psi l\nu X$, updates of b hadrons lifetime measurements, with a description of the B_s lifetime measurement, the $B_d^0 - \overline{B}_d^0$ mixing results and the limits set on rare B decay branching ratios. Current results are used to extrapolate B physics prospects for the future high luminosity run II.

1 Introduction

At the Fermilab Tevatron proton and antiproton beams are collided with a center of mass energy of 1.8 TeV. This is a very favorable environment to study B physics because the production cross section for b quarks is large and the resulting number of produced b hadrons is huge. An extrapolation from CDF cross section measurements indicates a total cross section of about 30 μb in the central region ($| \eta | < 1$), where CDF has most of its muon and tracking coverage. For typical Run I instantaneous luminosities (10^{31} cm^{-2}sec^{-1}) the $b\overline{b}$ production rate was 300 Hz, which was one order of magnitude larger than the CDF data logging rate. During run I the Tevatron delivered an integrated luminosity of 110 pb^{-1}: summing the neutral and charged species and including antiparticles, this corresponds to a total of about 10^9 B mesons produced in the central region with a transverse momentum greater than 6 GeV/c. Although B production is very copious, the problem of extracting a signal from background is particularly serious: the total inelastic $p\overline{p}$ cross section is 10^3 times larger than b production cross section and b production is peaked at low p_t, where most backgrounds are concentrated. This problem is faced in two steps: the trigger and the offline analysis. CDF based its run I trigger strategy on leptons:

- dilepton triggers: either two muons with $p_t >$ 2-3 GeV/c, or one muon with $p_t > 2$ GeV/c and one electron with $E_t > 5$ GeV;

- single lepton triggers: one muon with $p_t > 7.5$ GeV/c or one electron with $E_t > 8$ GeV;

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Dilepton triggers are used to select resonant states (J/ψ, $\psi^{'}$, Υ) and reconstruct exclusive b decays ($B \to J/\psi K$), or (away from resonances) for mixing studies and rare decays search. Single lepton triggers are the source of semi-exclusive b-hadron semileptonic decays used for lifetime measurements.

The CDF detector has been described in detail elsewhere[1]. The subdetectors which are relevant for B physics are the tracking, the muon systems and the electromagnetic calorimeter. The main components of the tracking system are the Silicon Vertex Detector[2] and the Central Tracking Chamber, which are contained in a 1.5 T magnetic field produced by a superconducting solenoid. Electrons are detected as showers in the electromagnetic calorimeter which surrounds the solenoid. Muons are detected by sets of drift chambers located in the back of the central calorimeter modules. The tracking system has excellent momentum and impact parameter resolution: $\sigma_{p_t}/p_t^2 \sim 10^{-3}$ and $\sigma_d = (40/p_t + 13)$ μm (p_t in GeV/c).

2   Observation of the B_c meson

The B_c meson is the bound state of a beauty and a charm quark. Nonrelativistic QCD potential models and the spectator model are expected to give a reliable description of its spectroscopy[3] and an estimate ot its lifetime[4]: the mass is expected between 6.2 and 6.3 GeV/c^2 and, depending on the adopted model, the lifetime is estimated between 0.4 and 1.4 ps. Although significantly shorter than other B mesons, the B_c lifetime is expected to be measurable with the CDF Silicon Vertex Detector. Fragmentation models predict that B_c production is suppressed by a factor of the order of 10^{-3} with respect to B_d and B_u mesons.

The most favorable and clear experimental signature is the decay into final states which include a J/ψ which have also a total branching ratio of the order of 20 %. We report here CDF search for the decay $B_c \to J/\psi l\nu$ where the lepton is either a muon or an electron[5][6]. The J/ψ is reconstructed through the decay $J/\psi \to \mu^+\mu^-$ which is selected at trigger level. The two muons and the third lepton are constrained to come from a common displaced vertex. Due to the presence of the neutrino in the final state, the only measurable quantities are the mass and the pseudoproper decay length of the trilepton system ($M(J/\psi l)$ and $ct^* = \frac{L_{xy} \times M(J/\psi l)}{p_t(J/\psi l)}$, where L_{xy} is the distance between the reconstructed decay vertex and the average beam position in the transverse plane). From Monte Carlo studies, which assume a B_c mass of 6.27 GeV/c^2, most signal events are expected to have $4 < M(J/\psi l) < 6$ GeV/c^2. To select possible decays of long lived particles a lower threshold on ct^* at 60 μm is set. The ct^* cut is chosen at about 1σ from zero (SVX provides a vertex position

Table 1. Summary of background sources and estimate of signal events for a $J/\psi l$ mass between 4 and 6 GeV/c^2.

	$J/\psi\ e$ results	$J/\psi\ \mu$ results
False Electrons	$2.6 \pm 0.05 \pm 0.3$	
Conversions	$1.2 \pm 0.8 \pm 0.4$	
Total False Muons		$6.4 \pm 0.5 \pm 1.3$
Punch-Through		$0.88 \pm 0.13 \pm 0.33$
Decay-in-Flight		$5.5 \pm 0.5 \pm 1.3$
$B\overline{B}$ bck.	1.2 ± 0.5	0.7 ± 0.3
Total Background	5.0 ± 1.1	7.1 ± 1.5
Events observed in data	19	12
Net Signal	14.0	4.9
$P_{Counting}$(Null)	2.1×10^{-5}	0.084

resolution of 50 μm) in order to have higher efficiency on signal. This cut has beeen removed for the lifetime measurement.

Starting from a sample of 196,000 J/ψ reconstructed in SVX and after rejecting candidates compatible with being $B^+ \to J/\psi K^+$ decays and events where the electron was identified as coming from a photon conversion, a sample of 31 J/ψ-lepton candidates (19 $J/\psi e$ and 12 $J/\psi \mu$) is found. A correct understanding and estimate of backgrounds is essential to claim that B_c is found. The main sources of background are expected to be due to real J/ψ which form a good displaced vertex when paired to a hadron misidentified as third lepton, and to $b\overline{b}$ events with one b hadron decaying to a J/ψ and the other b hadron decaying semileptonically, with a topology of the event compatible with having the J/ψ and the lepton exiting from the same vertex. Hadrons misidentified as the third lepton are found to be the main source of background. For muons this is due to light hadrons (pions or kaons) which punch-through the calorimeter and are then detected in the muon chambers, or decay in flight and produce a muon with a kink small enough to be well linked to the track of the hadron. For electrons this happens when the shower of a hadron in the electromagnetic calorimeter is undistinguishable from that of an electron. The contribution of these sources is estimated in the following way: starting from the J/ψ-lepton sample, the parent J/ψ-track sample is obtained releasing the lepton identification criteria on the third track; this sample is then weighted with the probability, estimated from real data as a function of p_t, that a hadron is misidentified as lepton. With this method also the mass shape of background can be obtained. Real $J/\psi l$ background from $b\overline{b}$ events is estimated from Monte Carlo simulation. Other possible sources of background are electron production from photon conversions and events with
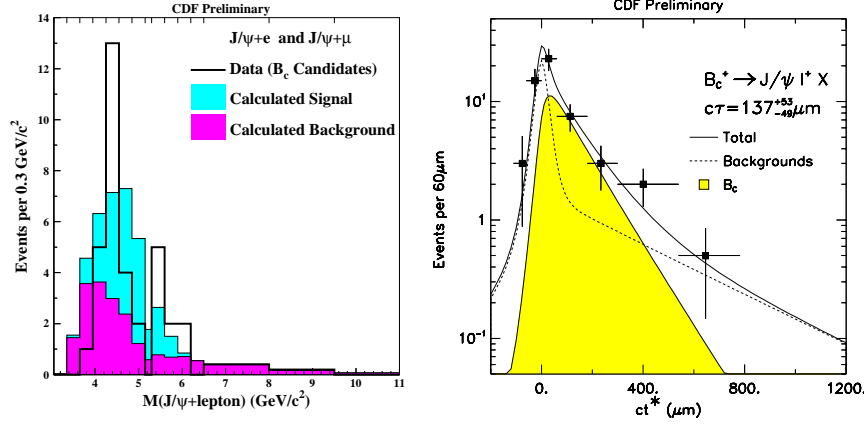
Figure 1. Left: Mass distribution of B_c candidates. The result of the fit for B_c signal (blue) and measured backgound (magenta) is superimposed. Events found to be compatible with being a $B^+ \to J/\psi K^+$ decay, when the kaon mass is assigned to the lepton, are rejected. These events would fall in the narrow $J/\psi l$ mass bin. Right: Lifetime distribution for data (crosses) with the result of the fit for signal (shaded histogram) and background (dashed line). The long lifetime component in the background distribution is due to B decays.

false J/ψ paired to a real lepton. A summary of all background sources and of the estimated signal in both channels is reported in Table 1.

The number of B_c mesons and the statistical significance of the excess is also estimated from a likelihood fit of the $J/\psi l$ mass distribution (fig. 1). The mass shape for signal and for background are respectively constrained to the results of signal simulation and of background measurement. The only free parameter returned by the fit is the number of B_c mesons, $N(B_c) = 20.4^{+6.2}_{-5.5}$. Signal significance is determined generating simulated experiments with no signal and the same level of background as data and counting how often the fit returns a value for $N(B_c)$ greater or equal than 20.4. The null hypothesis is rejected at the 4.8σ level.

To determine the B_c mass, the observed $J/\psi l$ mass distribution is fit for assumed B_c masses between 5.5 and 7.5 GeV/c^2. The dependence of the likelihood on the B_c mass shows a shallow minimum and provides the result:

$$M(B_c) = (6.40 \pm 0.39(stat.) \pm 0.13(syst.))\ GeV/c^2 \qquad (1)$$

This result confirms the initial value assumed for the mass (6.27 GeV/c^2). To determine the lifetime, the cut on the pseudoproper decay length (initially set

at 60 μm) is dropped. The new ct^* distribution (fig. 1) is fitted assuming that the background is parametrized by a prompt contribution plus a negative and a positive exponentials, while the signal is parametrized by a sigle positive exponential on which a statistical correction for the missing neutrino p_t is applied. Both background and signal distributions are convoluted with the experimental resolution on the decay length. The fit returnes:

$$\tau(B_c) = (0.46^{+0.18}_{-0.16}(stat.) \pm 0.03(syst.)) \ ps \tag{2}$$

A measurement of the B_c production cross section times branching ratio is performed with respect to B^+ production times $B^+ \to J/\psi K^+$ decay rate. This is done in order to cancel several systematical uncertainties and we find:

$$\frac{\sigma(B_c^+) \cdot Br(B_c^+ \to J/\psi l^+ \nu)}{\sigma(B_u^+) \cdot Br(B_u^+ \to J/\psi K^+)} = 0.132^{+0.041}_{-0.037}(stat.) \pm 0.031 \ (syst.)^{+0.032}_{-0.020}(lifet.) \tag{3}$$

3   Lifetimes

B mesons lifetime measurements are very important to search for effects beyond the spectator decay model. The expected effects are much smaller than in the case of D mesons: a difference only of the order of 5-10 % is expected between B_u and B_d lifetimes. CDF has measured the lifetime of all the species of b hadrons. B_d and B_u lifetime has been measured both in fully reconstructed $B \to \Psi K$ exclusive decays[7] (Ψ is either a J/ψ or a $\psi(2S)$, K can be any of the following: $K^\pm$, $K^{*0} \to K\pi$, $K_s^0 \to \pi^+\pi^-$ or $K^{*+} \to K_s^0\pi^+$) and in partially reconstructed semileptonic decays[8] $B \to DlX$ (D can be any of the following: a) $D^0 \to K^-\pi^+$; b) $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$; c) $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+X$). The average of the two measurements gives the following results:

$$\tau(B_u) = 1.66 \pm 0.05 \, (stat \oplus syst) \ ps \tag{4}$$

$$\tau(B_d) = 1.52 \pm 0.06 \ (stat \oplus syst) \ ps \tag{5}$$

$$\tau(B_u)/\tau(B_d) = 1.09 \pm 0.05 \ (stat \oplus syst) \ ps \tag{6}$$

These measuerements are very competitive with the results from other experiments and are approaching the precision necessary to test non spectator contributions. An update of a previous B_s lifetime measurement[9] in the semileptonic channels will be here presented. We anticipate the result:

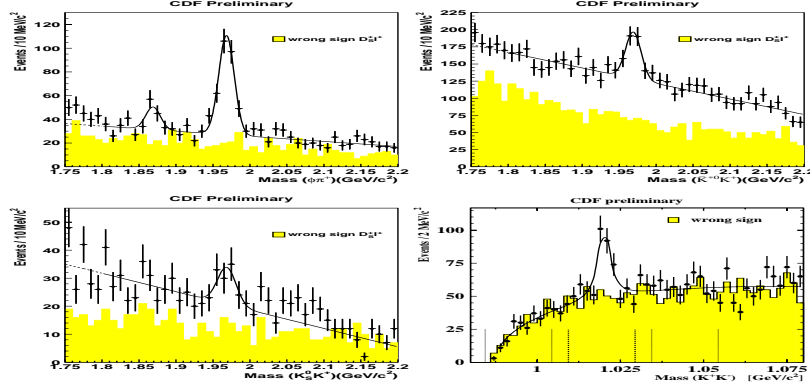$$\tau(B_s) = 1.36 \pm 0.09(stat.)^{+0.06}_{-0.05}(syst) \ ps \tag{7}$$

Figure 2. D_s invariant mass for the $B_s \to D_s^- l^+ \nu X$ events. Shaded histograms are the wrong sign $D_s l$ combinations which are used together with the D_s mass sidebands to determine the background shape in the lifetime fit. For the $D_s^- \to \phi \mu^- \nu$ channel the ϕ candidates mass is reported: in this case wrong sign combinations are $\mu^\pm \mu^\pm$ and $K^\pm K^\pm$ and the shaded histogram normalisation is rescaled to have the same number of signal and background events in the mass sidebands.

CDF has also measured Λ_b^0 lifetime[10] in the partially reconstructed decay $\Lambda_b^0 \to \Lambda_c^+ l^- X$, with the Λ_c^+ reconstructed in the resonant decay $\Lambda_c^+ \to K^- p \pi^+$. For completeness we also recall the result for B_c meson:

$$\tau(\Lambda_b^0) = 1.32 \pm 0.15(stat)\ 0.07(syst)ps \qquad (8)$$

$$\tau(\Lambda_b^0)/\tau(B_d) = 0.85 \pm 0.10(stat) \pm 0.05(syst)\ ps \qquad (9)$$

$$\tau(B_c) = 0.46^{+0.18}_{-0.16}(stat) \pm 0.03(syst)\ ps \qquad (10)$$

3.1 Measurement of B_s Lifetime

We present a new result obtained using the partially reconstructed semileptonic decay $B_s \to D_s^- l^+ \nu X$, with the lepton being either an electron or a muon. The D_s is reconstructed in four modes: a) $D_s^- \to \phi \pi^-$,

b) $D_s^- \to K^{*0} K^-$, c) $D_s^- \to K_s^0 K^-$, d) $D_s^- \to \phi \mu^- \nu$. Signal events are events with a $D_s l$ invariant mass between 3 and 5 GeV/c^2. We find about 600 such events. Mass plots for the four decay channels are reported in fig.2. Control samples for combinatorial background are obtained from the D_s mass sidebands and from wrong sign lepton-D_s combinations. A source of background is due to $D_d^- \to K^{*0} \pi^-$ and $D_d^- \to K_s^0 \pi^-$ events which can be reconstructed as D_s^- decays to $K^{*0} K^-$ and $K_s^0 K^-$. This is caused by the poor CDF particle identification. Due to low signal statistics, no attempt of reducing this background is performed. Instead, we introduce the estimated fraction of D_d^- events in the signal samples as a parameter of the final lifetime fit. This fraction is estimated using the large mass difference between D_d^- and D_s^- and the shape of reflections in the mass distributions. Intersecting the D_s and the lepton trajectories in the transverse plane, the B_s decay length is determined with a resolution of about 100 μm. A correction for the missing transverse momentum of the neutrino is applied event by event to obtain the proper decay time. The combined result of the four modes has been anticipated in eq. (7). This is the most precise measurement from a single experiment and it is lower by about 2σ than the current world average ($1.57 \pm 0.08\ ps$[11]).

4 Mixing

The Standard Model allows $B^0 \to \overline{B}^0$ transitions via higher order weak interactions contributions. As a consequence of this, a B^0 produced at $t = 0$ has a certain probability to mix into a $\overline{B}^0$ and viceversa. To measure this effect as a function of proper time, it is necessary to determine the B flavor at decay and production time and to measure the time of decay. When this can be done the frequency of mixing can then be determined from the following asymmetry:

$$A(t) = \frac{dN/dt_{B^0 \to B^0} - dN/dt_{B^0 \to \overline{B}^0}}{dN/dt_{B^0 \to B^0} + dN/dt_{B^0 \to \overline{B}^0}} = \cos(\Delta m t) \qquad (11)$$

where Δm is the mass difference between the B^0 and $\overline{B}^0$ states. Since it is possible to assign wrong tags, a mistag probability (P_0) has to be introduced and the measured asymmetry becomes $(2P_0 - 1) \cdot \cos(\Delta m t) = D_0 \cdot \cos(\Delta m t)$, with D_0 being the diluition of the tagging algorithm.

Experimentally the idea is to reconstruct one B in the $b \to c l \nu$ mode and tag the B flavor at decay time with the charge of the lepton. The time of decay is determined from the decay length in the same way as in the lifetime measurements. This is done using either exclusive D decay modes or inclusive

secondary vertexing techniques, which take advantage of a higher statistics but pay the price of a lower resolution on the decay time. The B flavor at production time can be determined from the away side b^a (using the lepton from the semileptonic decay, or a p_t-weighted charge average of the tracks in the b-jet), or from the tracks produced in the fragmentation of the same side b using the Same Side Tagging (SST) algorithm[12]. The SST method tags the B flavor using the charge of the pion produced with the minimum p_t^{rel} with respect to the system constitued by the B meson and the pion itself. CDF has recently measured B_d^0 mixing using this tagging technique[14] applied on a sample of partially reconstructed semileptonic decays $B^0 \rightarrow l^+ D^{(*)-} X$. The measurement determines simultaneously Δm_d and D_0:

$$\Delta m_d = 0.471^{+0.078}_{-0.068} \pm 0.034 \ ps^{-1} \tag{12}$$

$$D_0 = 0.18 \pm 0.03 \pm 0.02 \tag{13}$$

5 Rare decays

Evidence for physics beyond the Standard Model would result from an anomalous rate of rare decays like $B_d^0(B_s^0) \rightarrow \mu^+ \mu^-$. The theoretical prediction for the branching ratio is at the level of $10^{-10}(10^{-9})$[15]. Experimentally this channel is particularly favorable for the presence of the two muons which can be requested at trigger level, taking thus advantage of the copious B production provided by the Tevatron. The analysis basically requires the muon pair to come from a secondary vertex ($c\tau > 100 \ \mu$m) and to have an invariant mass within 75 MeV/c^2 (3σ) from the $B_d^0(B_s^0)$ mass. The request that B candidates are isolated, i.e. they carry most of the energy in the region surrounding the B candidates themselves, provides further background rejection[16]. A similar analysis is performed to set limits also on the branching ratio for the non resonant $B_u^+(B_d^0) \rightarrow \mu^+ \mu^- K^+(K^{*0})$ decays, for which the theoretical prediction is $0.4(1.0) \cdot 10^{-6}$. The following 90 % c.l. upper limits are found:

$$Br(B_d^0(B_s^0) \rightarrow \mu^+ \mu^-) < 6.8 \cdot 10^{-7} \ (2.0 \cdot 10^{-6}) \tag{14}$$

$$Br(B_u^+(B_d^0) \rightarrow \mu^+ \mu^- K^+(K^{*0})) < 5.4 \ (4.1) \cdot 10^{-6} \tag{15}$$

which are still far away (three orders of magnitude) from theoretical predictions for the $B_d^0(B_s^0) \rightarrow \mu^+ \mu^-$, while they are getting very close to constraining the theory in the $B_u^+(B_d^0) \rightarrow \mu^+ \mu^- K^+(K^{*0})$ case.

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^{a} "Same side b" is the b reconstructed in the $b \rightarrow cl\nu$ mode. "Away side b" is the other b produced in the $p\overline{p}$ interaction: it can be used to tag the B flavor at production time (away side tagging methods).

CDF has also searched for the non Standard Model $B_d^0(B_s^0) \rightarrow e^{\pm}\mu^{\mp}$ decays. The simplest model which incorporates the lepton flavor non-conservation and admits the existence of a new force that mediates transitions between quark and leptons is the Pati-Salam model[17]. This model predicts heavy bosons called Pati-Salam leptoquarks (LQ) which would mediate the decays $B_d^0(B_s^0) \rightarrow e^{\pm}\mu^{\mp}$ [18] [19]. Limits on branching ratios are set and limits on LQ masses are derived (at 90 % c.l.):

$$Br(B_d^0(B_s^0) \rightarrow e^{\pm}\mu^{\mp}) \ < \ 3.5(6.1) \cdot 10^{-6} \tag{16}$$

$$M_{LQ}B_d^0(B_s^0) \ > \ 21.7(20.7) \ TeV/c^2 \tag{17}$$

6 Prospects for run II

CDF strategy for run II upgrades is to optimize quality of information in the central region and expand coverage. A new 3D Silicon Vertex detector and an Intermediate Silicon Layers detector will be installed in order to improve tracking robustness and vertex finding ability in the central region and extend tracking capability to the forward region. The Silicon Vertex Tracker[20] will allow online tracking of the Silicon Vertex[13]. B samples statistics will result significantly increased by the possibility to trigger on secondary vertices and otherwise unexplorable channels will be accessible. The increased coverage of lepton detectors will improve B tagging efficiency in the leptonic modes. CDF goals for B physics in run II are the observation of CP violation, of B_s mixing and of rare and radiative B decays. Although the sensitivity on the recent $\sin(2\beta)$ measurement[b] from run I data is low ($\sin(2\beta) = 1.8 \pm 1.1 \pm 0.3$)[21], this result establishes the feasibility of measuring CP symmetries in B meson decays at a hadron collider. With the expectation of 20 times more integrated luminosity in run II and the improved detector performance, CDF has very good prospects to observe CP violation in the $B_d^0 \rightarrow J/\psi K_s$ and maybe also in the $B_d^0 \rightarrow \pi^+\pi^-$ decays.

7 Conclusions

Recent B physics results from CDF experiment based on data collected during the 1992-1996 run have been reported: the B_c discovery, an updated B_s lifetime measurement, a new measurement of Δm_d obtained with the Same Side Tagging technique, and new limits set on rare B decays branching ratios.

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[b] This result was not reported in these Proceedings because it was unpublished at the time of this Conference.

Extrapolations of current results give bright B physics prospects to the future high luminosity run II.

Acknowledgments

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